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ORIGIN OF A BOULDERY DIAMICTON, KUNLUN PASS, QINGHAI-XIZANG PLATEAU, PEOPLE'S REPUBLIC OF CHINA: GELIFLUCTION DEPOSIT OR ROCK GLACIER?

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ABSTRACT

On the west side of the military road to Tibet in the Kunlun Shan, a major body of diamicton is moving slowly downslope from the ridge crest at 4800 m in a northerly and easterly direction. The material is derived from Middle Pleistocene till deposits and the underlying Pliocene alluvial gravels. More than 10 per cent of the material is composed of boulders longer than 2 m, 45 per cent has long axes between 0·5 and 2 m, while the matrix is a poorly sorted sandy loam. The mean annual air temperature is −7°C to −5°C and the mean annual precipitation is under 300 mm a^{-1}. The diamicton lacks a vegetation cover, in contrast to meadow tundra on the surrounding slopes.

The diamicton mantles the north slope of the ridge, but splits into at least 16 separate tongues which are moving down fluvially graded valleys. The average slope of the landform is about 19°, while the mean slope of the fronts of the tongues is 21°. With one exception, the slope of the fronts does not exceed 25°, unlike true rock glaciers. The diamicton is up to 40 m thick in valley 4. The active layer was 12 to 30 cm deep in July at 4780 m, increasing to 1·5 to 2 m at about 4650 m. Ice contents in the permafrost may reach 57 per cent but 30 per cent is more usual.

The larger boulders act as braking blocks on the upper slopes of the landform and are frozen into the permafrost. The lower parts of the landform move at under 3 cm a^{-1}, whereas the fine-grained material in the active layer moves past the braking blocks on the upper slopes at up to 30 cm a^{-1}. There is no direct evidence for flowage of the icy diamicton forming the deposit. It is therefore best referred to as a gelifluction slope deposit, and is the longest and most spectacular of such deposits described so far in the world. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: Gelifluction; braking blocks; rock glaciers; Tibet; mountain permafrost

INTRODUCTION

A study of permafrost landforms along the military road from Golmud to Tibet, revealed a diamicton forming a gently sloping mass on the north and east side of the Kunlun Shan (Fig. 1) at latitude 35° 40′N, 94° 00′E (Cui, 1980, 1981, 1982, 1983a,b). The diamicton lay above the lower limit of continuous permafrost. The diamicton has been variously interpreted by Cui, first as a rock ice-cap or periglacial boulder tongue (Cui, 1981) and later as a new type of rock glacier, or a form of rock stream (Cui, 1983a,b). However, the rock glacier interpretation is now thought to be unlikely because the diamicton does not move as a continuous sheet, as is found in the case of rock glaciers (e.g. Blumstengel, 1988; Blumstengel and Harris, 1988; Gorbunov *et al*., 1992). The present paper describes the nature of the diamicton, re-evaluating its origin, and interpreting the diamicton as a gelifluction deposit based on visits in five of six years between 1990 and 1996.

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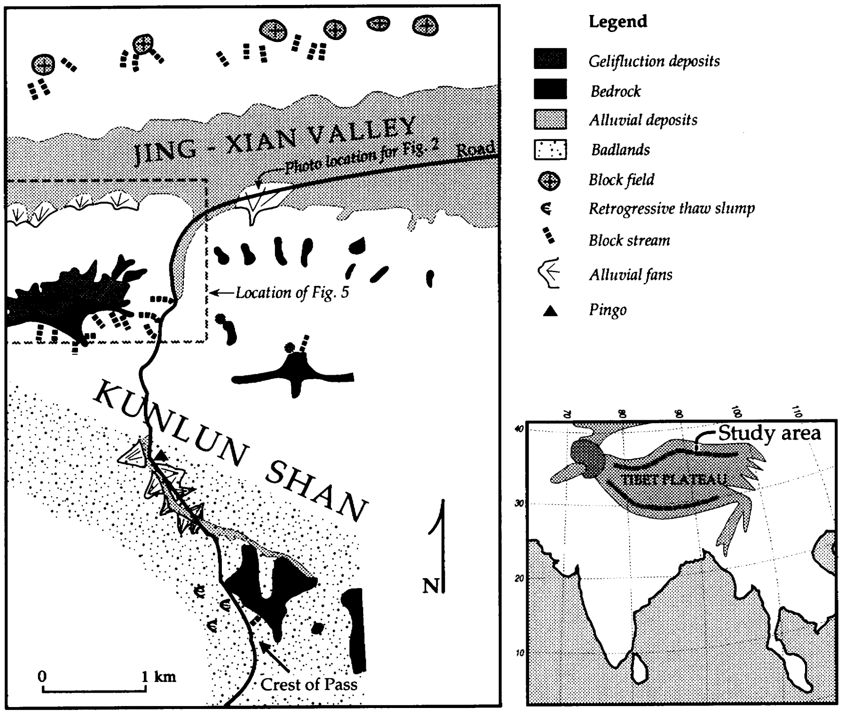

Figure 1. Location of the extensive diamicton on the northern slope of the Kunlun Shan (latitude 35°40′ N, longitude 94°00′ E)

Table I. Weather data for Xidaton (elevation 4101 m) for 1976 (Zhao Xiufeng, personal communication; Zhao Xiufeng *et al.*, 1993)

	Month												Year
	J	F	M	A	M	J	J	A	S	O	N	D	
Mean Air Temperature (°C)	−13·4	−11·3	−8·2	−2·8	0·6	4·9	5·9	7·4	3·8	−2·0	−10·0	−13·8	−3·2
Mean Precipitation (mm)	–	–	–	–	–	–	–	–	–	–	–	–	287

STUDY AREA

The large, structureless diamicton occurs on the upper part of the north-facing slope of the main range of the Kunlun Shan along the south side of the Jing-Xian valley (the Xidatan valley of Zhao Xiufeng *et al*., 1993). The main deposit lies west of the military road through the Pass (Figure 1) and ranges in elevation from 4800 m to 4570 m. To the east of the highway, two smaller diamicton deposits extend up to 5050 m, but these are always found below outcrops of Middle Pleistocene tills.

The climate of the area is cold and dry (Table I), the estimated mean annual air temperature being −5 to −7°C. and the mean annual precipitation less than 300 mm. Most of the precipitation occurs in summer as snow or rain, while the winters are cold and dry. The lower limit of continuous regional permafrost is probably at 4450 m (Cui, 1983b, p. 209), although locally the permafrost is of widespread island type. The slope faces north and east and permafrost is continuous under the diamicton.

The vegetation of the surrounding, more stable slopes consists of a meadow tundra extending up to 4700 m and an alpine tundra above this elevation. The diamicton, by contrast, is almost devoid of vegetation (Figure 2), with only individual plants of several species, mainly *Saussaurea* spp., actually grow on the moving material. The plants show stem/root elongation of up to 20 cm downslope, demonstrating that the surface of the diamicton moves faster than the layers below about 5 cm (Figure 3).

Figure 2. Photograph of the extensive diamicton from the northeast showing the lack of surface vegetation and the lobes extending down the valleys

Figure 3. Elongation of the root/stem of *Sausaurea hypsipeta* growing on the surface of the diamicton, demonstrating that the surface layers of the diamicton are moving faster than the underlying material. This is typical of gelifluction

A geological cross-section of the area is shown in Figure 4. The bedrock of the lower slopes consists of Triassic red sandstone overthrust by a sequence of Miocene gravels and Pliocene sands and gravels. These, in turn, are overlain by Middle Pleistocene till resulting from a more extensive glaciation of the area earlier during the Pleistocene (Gerasimov and Zimina, 1968; Shi Yafeng *et al*., 1979). Subsequent uplift of the Himalayas has reduced the main supply of moisture from the Indian Ocean, resulting in the present-day aridity and limited extent of cold-based glaciers.

The main Jing-Xian valley consists of a tectonically active, down-faulted trough trending east–west. The faulting commenced in the Early Pleistocene, with another major phase of movement in the Middle Pleistocene (Zhao Xiufeng *et al*., 1993). Subsequent violent movements are still occurring, and up to 310 m of alluvium has accumulated on the valley floor.

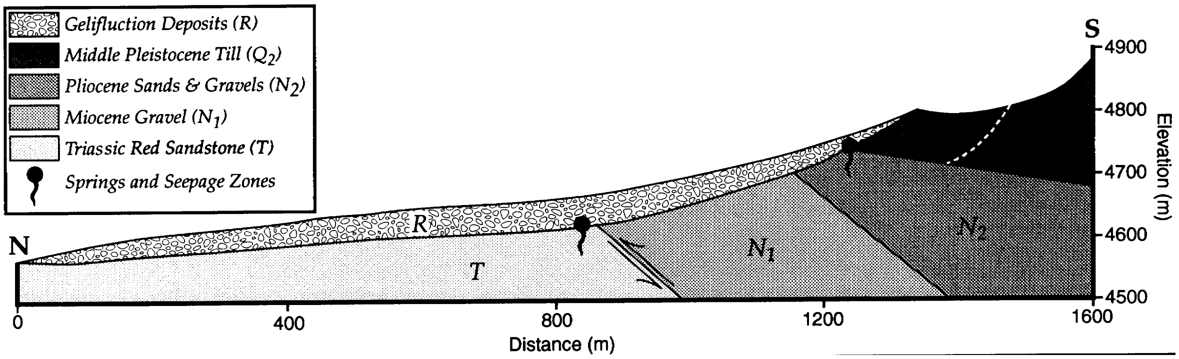

Figure 4. North-south cross section of the diamicton showing its relationship to the underlying bedrock (partly after Cui Zhijiu, 1993a)

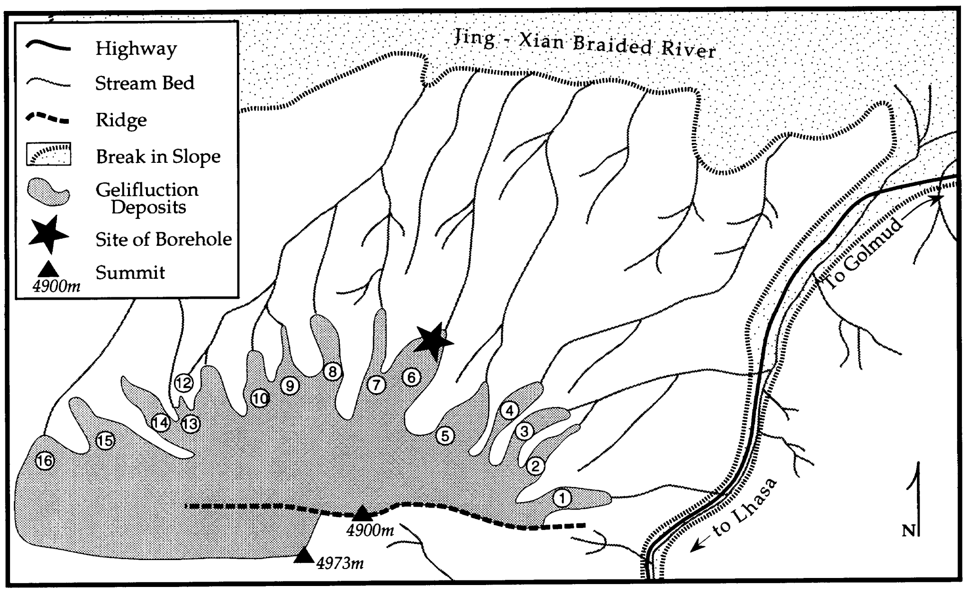

Figure 5. Map of the main active diamicton west of the military road from Golmud to Lhasa. It has 16 tongues extending down the valleys below the main deposit

Small springs and seepage zones are sometimes seen at the junction of the till and the underlying sands and gravels, but the water disappears into the diamicton. There is little water flowing in the gullies cut into the slopes below the diamicton except after precipitation events, so the spring water may become part of the ice in the diamicton.

RESULTS

Morphology

The morphology of the main diamicton consists of a shield-like slope deposit in the upper parts with 16 tongues extending down the gullies cut into the Triassic rocks on the lower mountain slopes (Figure 5). The gullies are generally steep-sided and the diamicton is extending downhill, inundating the valley bottoms (Figure 6). The tongues were regarded as individual rock glaciers by Cui (1983a,b, 1985). Shapes and slope data for the tongues are given in Tables II and III.

The upper part of the main diamicton consists of the rounded northerly slopes of the outcrop of the Middle Pleistocene till. It ranges from 4900 m at the ridge crest down to about 4750 m, and has slopes as steep as 30° in places. Below this is a wide, extensive, more gentle surface averaging about 15–18°. Photographs show that this extensive cover is relatively smooth (Figures 1 and 7), and material moves from this zone into the upper parts of

Figure 6. Close-up of the relationship of tongues 4 (a) and 5 (b) to the valley walls. Note the relative lack of vegetation on the tongues

the fluvial gullies downslope. Where it does so, a minor concavity is developed and the profile of the deposit steepens as the diamicton moves to fill the upper part of the gully. The average slope of the deposit in the gullies is 20·7°, but only one gully (no. 4) exhibits the diamicton with a frontal slope greater than 24°.

There is no obvious oversteepening of the fronts of the type found in rock glaciers (>33°), but in gully no. 4, the present front appears to be overriding another thin deposit of similar material which extends 100 m further downvalley. This was interpreted by Cui (1983b, p. 210) as indicating two periods of movement separated by a break, but the exact cause of this feature (catastrophic flood, climatic change, or tectonic action) has yet to be determined.

In detail, the upper and main slopes of the shield-like diamicton exhibit shallow lobe-like features of diamicton when partly covered by melting summer snows (Figure 8), indicating that some form of lobal movement has taken place.

Table II. Elevation of terminus, orientation and shape of the congelifluction lobes below the main diamicton (after Cui, 1993a,b)

Congelifluction lobe no.	Elevation of terminus (m)	Orientation	Rate of movement (cm a^{-1}) 1980–82	Length (m)	Width (m)	Length/width
1	4670	E	0·2–0·3	350	84	4·17
2	4740	NE	n.d.	240	24	10·00
3	4700	N 45° E	n.d.	396	78	5·08
4	4700	N	2–3	408	120	3·40
5	4680	N	n.d.	438	120	3·65
6	4700	N	n.d.	420	204	2·06
7	4670	N 30° E	n.d.	408	50	8·16
8	4710	N 30° E	n.d.	276	20	13·80
9	4650	NE	n.d.	396	120	3·30
10	4750	N 40° E	n.d.	156	25	6·24
11	4730	NE	n.d.	204	48	4·25
12	4660	NE	n.d.	216	96	2·25
13	4760	NE	n.d.	108	120	0·90
14	4610	E	n.d.	240	120	2·00
15	4570	N 20° E	n.d.	324	150	2·16
16	4610	E	n.d.	180	204	0·88

Table III. Average gradients of the 16 congelifluction lobes below the main diamicton at Kunlun Pass (data after Cui, 1993a, p. 69)

Slope (degrees)	Active lobes				Transitional lobes				Inactive lobes				
	4	7	1E	2	1W	5	6	10	3	6	8	11	5
Terminus	37	22	28	27	20	18	19	24	18	18	17	18	10
Middle	15	19	22	19	20	21	15	18	18	18	12	14	12
Upper	35	24	29	28	13	17	18	15	18	18	14	18	12
Mean of all the group	25°				18°				15°				

Figure 7. View north over the surface of the main diamicton to the Jing-Xian valley, showing the relatively smooth surface of the diamicton except for large blocks up to 3 m long. Note that the surface of the diamicton is depressed above the commencement of the tongues (arrows), indicating flowage into the valley below

Figure 8. Shallow lobe-like features on the surface of the main diamicton which appear first during the melting of summer snowfalls

Locally where springs occur, slight gullies and subsidence features are found, but the water quickly disappears into the diamicton. This may result in the formation of subsidence features elongated downslope and aligned with the springs.

Lithology and grain size

At least 50 per cent of the material consists of large boulders ranging up to more than 2 m in length down to small pebbles. Of these, 10 per cent exceed 2 m in length, 45 per cent have long axes of 0·5–2 m, 30 per cent have long axes of 0·1-0·5 m and 15 per cent are 0·02–0·10 m in length. Of the <2 mm fraction, 53–56 per cent by weight falls in the 0·1–2 mm range and 41–47 per cent in the 0·005–0·100 mm size group. Clay ($<0{\cdot}005$ mm) never exceeds 0·1 per cent.

The lithologies of the angular boulders range from granites and granodiorite to pyroxenites. All these occur in the till.

Active layer thickness and permafrost

On the sloping surface of the Middle Pleistocene till, just below the crest of the ridge, the depth of the frost table ranges from 12 to 30 cm in July. Within the diamicton, this increases downslope to 30–60 cm at 4700 m and to 1·5 to 2 m at about 4650 m. Permafrost appears to occur everywhere within and below the diamicton. Drillholes near the terminus of the diamicton in valley 6 indicated temperatures of -2°C at 39 m depth in 1982, showing that the permafrost extends well into the underlying bedrock, even near the terminus of the diamicton.

Thickness of the diamicton

Cui (1983b) carried out electrical resistivity profiles on the diamicton in valleys 1 and 4. In valley 1, where the front of the diamicton is almost stationary, a marked change in resistivity occurred at a maximum depth of 25 m. In the very active valley 4, the comparable break was encountered as low as 40 m depth in places. These are regarded as indicating the maximum thicknesses of diamicton at these locations.

Ice/moisture contents

Between summer precipitation events, the surface of the active layer may have a 5–10 per cent moisture content by weight, in contrast to snow melt events, when the moisture content immediately downslope of the snow locally reaches 30 per cent by weight, exceeding the liquid limit. This is when flowage occurs. Moisture

Figure 9. Localized gelifluction occurring over the underlying frozen diamicton, producing a broad, creeping lobe front (beneath the right foot of the man) due to saturation by melting snow

content usually increases with depth in the active layer, so that moisture contents may be more than 40 per cent immediately above the frozen ground.

Ice contents of 29 per cent and 57 per cent were measured in permafrost at depths of 25 m and 39 m in diamicton along valley 6 (Cui, 1983b). The drill site was near the terminus (Figure 5) and the ice was interpreted as frozen rain and snow.

Movement of the diamicton

Attempts at measurement of rates of movement of material on the slope of the Middle Pleistocene till were unsuccessful. Painted stones rolled downslope and painted lines, plastic tubes and stakes disappeared completely in a year. Clearly rates of erosion are high.

Melting snow produces substantial local wetting of the upper part of the diamicton, resulting in small-scale gelifluction over the underlying frozen material (Figure 9). In extreme cases, short, small scale debris flows may occur (Figure 10). The finer material tends to move faster than the larger blocks. Large blocks frozen into the main diamicton act as braking blocks (Figure 11). Congelifluction is dominant and sorting is minimal.

Measured rates of surface movement of painted boulders near the ends of the tongues varied from 0·225 to 0·36 cm a^{-1} in valley 1, to 2–3 cm a^{-1} in valley 4 (Cui, 1983a,b). Three categories of movement have been identified: active (tongues 4, 7, 1 east and 2); transitional (tongues 1 west, 5, 6 and 10) and inactive (tongues 3, 6, 8, 11 and 5 east) (Cui, 1983a,b; see Table III). Active tongues generally had an average slope of 25°, transitional tongues of 18° and inactive tongues 15°. Even Cui's inactive tongues lack appreciable vegetation growth as well as lichens on surface stones. By contrast, lichens are common on the surfaces of stones in the alpine meadow.

In the middle of the diamicton, flowage of surface material overlying frozen diamicton, as in Figure 9, may reach speeds of up to 0·5 cm min^{-1} for short periods and may result in the finer material tending to flow past the larger blocks. Total movement in a flow event rarely exceeded 20 cm. Extremely rapid mud flows of the type shown in Figure 10 only extend 1–2 m in length and are up to 8 cm wide, and therefore involve very little material. They tend to be located close to springs.

The larger braking blocks (Figure 11) were used to estimate rates of flowage of material past them by repeating photography each year from 1990 to 1996. The average rate of relative movement was estimated at about 30 cm a^{-1}, although the rate depends on the grain size: the larger the material, the slower the movement. Rates of creep of the icy permafrost were not measured.

Figure 10. A small-scale debris flow produced by saturation from melting snow

Figure 11. A large braking block on the surface of the main diamicton. The finer surface material is flowing past and around it since the large block is frozen into the underlying permafrost. Note the cavity in the surface below the large block

DISCUSSION AND CONCLUSIONS

The diamicton is clearly a local slope deposit formed in continuous permafrost beneath a Middle Pleistocene diamicton. It occurs at altitudes of 4570–5050 m on north- and east-facing slopes in areas of good drainage. Most of the limited precipitation consists of summer snow, which melts, producing localized but short-lived high moisture contents in the active layer. This results in congelifluction and minor localized debris flows.

Fastest rates of movement occur at the crest of the feature and decrease towards the terminus. There seems to be a relationship between speed of movement of the tongues in the valleys beneath the diamicton and the

surface slope. Rates of advance (0·225 to 3 cm a^{-1}) are typical of gelifluction/congelifluction deposits, and the coarser debris moves more slowly. Large boulders act as braking blocks in the middle and upper parts of the landform. In general, the material lacks vegetation in marked contrast to the adjacent meadow tundra.

This evidence implies contrasting rates of movement of material spatially over and within the landform. Most movement is in the active layer, where it is often quite rapid. This is in marked contrast to the sheet-like movements observed in active rock glaciers (Blumstengel, 1988; Blumstengel and Harris, 1988; Gorbunov *et al*., 1992). There, a whole mature forest may be carried on a rock glacier moving at speeds up to 2 m a^{-1} without noticeable damage to most of the trees. The speeds of movement in rock glaciers are up to two orders of magnitude faster, while they appear to require rather more humid climates (Harris, 1994). Finally, there is no sign of an oversteepening of the front of the lobes at the Kunlun diamicton, such as is found in rock glaciers.

Given the substantial differences, it seems reasonable to conclude that the diamicton at the Kunlun Pass is not a rock glacier but a giant gelifluction slope deposit forming where there is an unusually fortuitous set of circumstances involving abundant source material (the Middle Pleistocene till), perched on top of a steep north-facing slope exceeding 200 m in height, and a climate cold enough for permafrost to develop. What is important about this is that it shows that gelifluction can be very effective in forming a large landform on a slope in a relatively dry, cold climate if the precipitation regime is suitable.

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